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A PROPOSAL FOR THE STUDY OF COLLISIONAL PROCESSES LEADING TO ELECTRONIC EXCITATION AND IONIZATION BEHIND SHOCKWAVES

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UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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NOLTR 63-33 5 May 1963

A PROPOSAL FOR THE STUDY OF COLLISIONAL PROCESSES LEADING TO ELECTRONIC EXCITATION AND IONIZATION BEHIND SHOCKWAVES

This report presents the proposal to study the fundamental collisional processes which lead to ionization and electronic excitation behind strong shockwaves by means of alkali metal vapors.

The knowledge gained, both experimentally and theoretically, will be helpful in the understanding of the much more complex collisional processes occurring in air around re-entry bodies.

The proposal was accepted for support under the Foundational Research Program at the Naval Ordnance Laboratory and work on this program is currently being performed under NOL Task Number FR-64.

R. E. ODENING
Captain, USN
Commander

A. E. Seigel
A. E. SEIGEL
By direction

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ILLUSTRATIONS

REFERENCES

(1) Pomerantz, J. and Piacesi, R., "The Equilibrium Composition and Thermodynamic Properties of Sodium Vapor from 400° to 10,000°K," NOLTR 62-170 (in publication)

(2) Encyclopedia of Physics, Vol. XXII, Gas Discharges II

(3) Burhorn, F., Maecker, H., and Peters, T., Z. Physik 131, 28(1951)

proposal for studying the phenomena under more ideal conditions in a novel laboratory facility.

PREVIOUS INVESTIGATIONS AND AVAILABLE TEST FACILITIES

The most successful tool for producing strong shockwaves, with well-known conditions immediately behind the shock front, is the shocktube. It has therefore been used quite extensively to study ionization and electronic excitation phenomena, particularly in monatomic gases.

All the early investigations showed that spectral lines of impurities appeared before any of the lines of the test gas became discernible in the spectrograms. This indicated that the process of adjustment to the high temperature equilibrium involved in the first step only the molecules of the impurities which have the lower excitation levels. The presence of excited states of the impurities and their electrons will influence the subsequent adjustment of the test gas. The electrons will speed up the adjustment because they are very efficient in accomplishing transitions. Transfer of excitation from the impurity molecules to the molecules of the test gas which may occur would also lead to an accelerated adjustment.

Using spectroscopically pure gases and flushing the shocktube repeatedly prior to the test reduces the content of impurities to a level sufficiently low to escape detection under the condition of very short observation time. However, even in this case the impurity originated electrons and excited states could still be sufficient in numbers to trigger and hasten the adjustment process of the test gas. An investigation of the collisional processes leading to ionization and electronic excitation in a shocktube must therefore be viewed with caution.

Wind tunnels are well-established facilities for the study of flow phenomena under stationary conditions. The production of high stagnation temperature flows has, however, not yet been too successful, if requirements for the absence of impurities are stringent. Since all such tunnels use electric arc heating to achieve the required high energy levels, electrode-introduced impurities are of major concern. Neglecting for the moment the electrode-introduced impurities and those originally in the test gas, other impurities which may be called inherent may still be present in the arc-heated test gas. They may be produced within the originally pure test gases by the process employed to achieve the needed stagnation enthalpy and then remain in the test gas, because the expansion in the nozzle is too fast for adjustment. Others may be formed during the

expansion process. The kinds of inherent impurities which will be present depend on the test gas or gas mixture being used. In the case of air these inherent impurities may be the nitrous oxide, metastable electronic states and other excited states of long relaxation times.

It can be expected that the different kinds of impurities will, to a varying degree, have an effect on the adjustment processes here under consideration.

With regard to the proposed studies, the shocktube must be regarded unsuitable because a definite evidence of the absence of impurities can most likely not be secured in the very short testing time typical for these facilities. Wind tunnels, on the other hand, could provide very long testing times to study even very faintly luminous flows.

If it would be possible to eliminate the impurities from the flow, then an arc-heated wind tunnel would be preferable for the proposed studies.

NEW APPROACH

Monatomic substances which are gases at normal pressure and temperature, namely, the noble gases, do not meet the requirements of a test gas as set forth in the previous section. The most serious restriction is their fairly high ionization potentials. In addition, they exhibit metastable states. The vapors of the alkali metals Na, K and Cs appear to be a better choice, as will be evident from their characteristic properties (fig. 1).

The alkali metal vapors have the lowest ionization potential of all "gases." Impurities, if present in easily controllable amounts do not effect the onset of ionization.* The spectra of the alkali elements are relatively simple and exhibit the resonance lines in the visible region. The alkali atoms have no metastable states. It can therefore be expected that the expansion from reservoir condition to a supersonic flow leads to a completely relaxed monatomic gas, because the de-excitation from the electronic and ionization levels does not require collisions but can proceed mainly through radiative recombination for which the mean life time is in the order of 10^{-8} seconds.**

* In a closed test facility impurities can be completely eliminated by utilizing the capability of the alkali metals to act as getters.

** Under certain conditions (see ref. (1)) a very small percentage of molecules may be present in the expanded gas.

Another advantage of utilizing alkali metal vapors becomes apparent with respect to the theoretical determination of the collision cross sections. With only one electron outside of closed shells the solution to the various wave functions representing the ground state, the excited states as well as the ion become more amenable for treatment. Knowing the wave functions the transition probabilities between the various electronic states can be evaluated. Finally, the various collisional cross sections could then be determined.

If the cross sections had been theoretically calculated as indicated above, the adjustment process of equilibrium ionization and electronic excitation could be determined and could be expressed in experimentally observable quantities. Unfortunately, this calculation is not yet available and will not be available in the near future because of the large effort involved in the computations. Therefore, theoretical efforts which should be done to supplement the experimental investigations should concentrate first on the calculations of those cross sections which the experiments show to be the most important or the most interesting ones. A comparison of the calculated and observed collisional cross sections will be indicative of the degree of confidence one can have in the approximation used to evaluate the associated wave functions.

PROPOSED TEST FACILITY

As implied in the previous discussions, an alkali metal vapor test facility would essentially be an arc-heated wind tunnel in which the flow conditions necessary for the proposed studies can be produced. It will, however, distinguish itself from the high-enthalpy arc-heated air wind tunnel because of certain properties of its working fluid. Of particular interest is that the working fluid is an electrical conductor in the solid and liquid state, a nonconductor in the gaseous, non-ionized state, and a conductor again in the gaseous, ionized state.

This brings about several advantages for the alkali metal vapor arc tunnel which relate to its design and operation. The working fluid, in its liquid state, can be used as electrodes. Evaporation from the electrodes can supply the system with the working fluid, thereby eliminating the impurity problem.

The alkali metal vapor tunnel can, in principle, be designed similar to an air arc-heated tunnel. The arc discharge would take place between two suitably shaped pools of liquid alkali

metal. The arc-heated vapor would enter a settling chamber from which it would expand through a nozzle into a test chamber. The arc would be started in an argon atmosphere which would be gradually removed as the vapor pressure of the alkali metal increases. The vapor pressure in the reservoir reaches its maximum when it equals the saturation vapor pressure at the temperature of the reservoir chamber. The reservoir pressure is thus restricted to a level for which the reservoir temperature is low enough to prevent reactions between the chamber material and the particular alkali metal in use. The stagnation temperature is also restricted because of the conduction and radiation losses in the settling chamber and because of the mixing of the heated gas with cooler vapors.

In the following, suggestions are made for arrangements which are less restrictive with respect to the temperature and pressure. To obtain higher stagnation temperatures, the temperature of the arc column should be increased. This can only be done by constricting the arc column (ref. (2)). To take full advantage of the temperature increase, the constricting opening should also be utilized as the orifice of a supersonic jet or the throat of a supersonic nozzle.

An electrode arrangement as shown in figure 2 for the case of a jet is suggested. An alkali metal pool in the reservoir chamber (A) is used as the cathode. A cover plate (B) with an orifice in its center which is electrically insulated (C) from the container (A) holding the pool completes the reservoir chamber. To avoid attachment of the arc to the metallic cover plate, its thickness must be restricted. The condition is that the change in the potential in the arc column over the thickness of the constricting plate must be smaller than the cathode and anode potential drop taken together.

Above the orifice a doughnut-shaped anode (D), which is cooled internally, is placed as shown in figure 2. The attachment of the arc to this electrode will be diffused over at least the inside of the electrode due to the low pressure in the test section needed for the proposed investigation. The heat load will therefore be uniformly distributed and sufficiently low to prevent, by internal cooling, melting of the electrode material.

A very effective cooling is needed at the orifice where temperatures and densities are higher. But even with the most effective design of internal cooling, melting of the metal wall limits the degree of constriction and thus the temperature of the constricted portion of the arc channel.

To circumvent this limitation, a water pipe has been utilized (ref. (2)) where the extreme heat-transfer rates are taken up by evaporation cooling. The water pipe is formed by centrifugal forces in an arrangement as shown in figure 3. The water enters a pillbox-shaped container tangentially and leaves at openings in the center of the cover plates (E) with greatly increased rotational speeds. In spite of high rates of evaporation, a uniform cross section constriction of the arc discharge is maintained. Maecker (ref. (3)) was very successful in using the device and was able to produce temperatures of 50,000°K.

It is suggested here to utilize the device in the design of an alkali metal vapor arc tunnel. The water which, of course, could not be used would be replaced by the liquid alkali metal. In doing so, there seems to be no apparent reason why a liquid metal should not perform satisfactorily even though the liquid metal would not wet the material of which the device is made, as water does.

The device could serve as an orifice or as an electrode. As an orifice the same restriction on the length for non-attachment of the arc applies, as previously mentioned, since the liquid forming the pipe is electrically conducting.

As an electrode, however, one should use a long constriction with the arc attached in the center portion where the outward velocity remains small. This portion will reach higher temperatures than the end portions and thus surface temperatures can be produced where electron emission takes place. The arc should remain attached to the center region because in the outward regions evaporation will occur without leading to ionization and the discharge channel should become insulated from the liquid metal pipe. The liquid pipe electrode should be used as the cathode.

There will be interactions between hydrodynamic and electromagnetic forces. The resulting effects are difficult to estimate since the electric current flows radially in the liquid metal and axially in the plasma. Some experimental investigations will indicate the restrictions imposed due to the magnetohydrodynamic forces.

An advantage of the proposed electrode is that it acts as a reservoir system. Higher pressures can be produced in it than in a reservoir chamber with its restricted temperature range.

The anode can be a doughnut-shaped electrode (D), as has previously been described (fig. 4 and 2). Two jets are ejected

from the liquid pipe electrode when it is in operation. Of particular interest is the jet emerging in the direction opposite to the anode. This jet will be of lower enthalpy since it is not subjected to the heating from the arc discharge, but its expansion is not obstructed by the presence of an electrode.

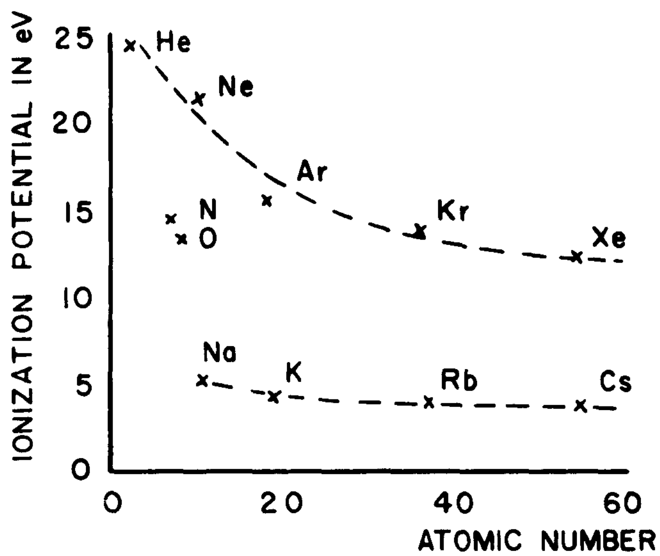
The development of a suitable electrode system will probably require many trials before a successful arrangement may be achieved. In view of the difficulties encountered in handling of and experimenting with alkali metals, it may be advisable to substitute, wherever possible, mercury for the alkali metals in the development of a suitable electrode system.

MEASUREMENTS

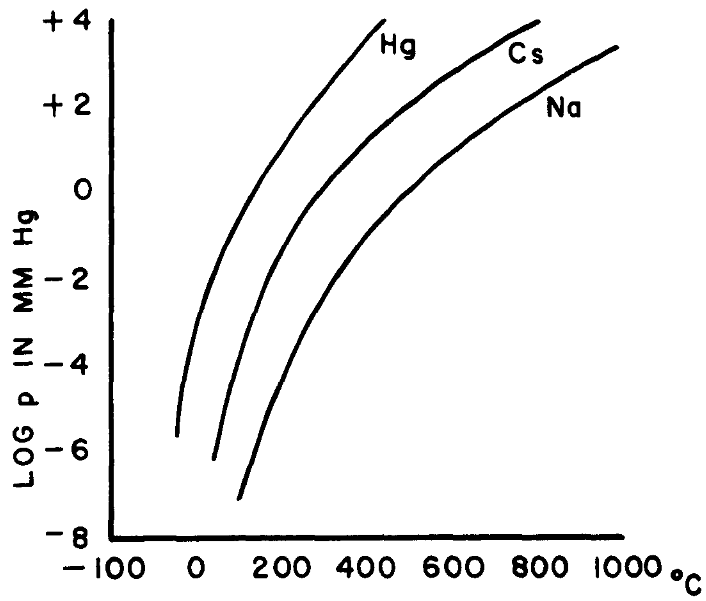
It is proposed that initially all investigations of the onset of electronic excitation and ionization and the approach to thermal equilibrium will be made behind stationary shock-waves on wedges. Almost all data on the temperature, pressure, density, composition, and flow velocity of the test gas will be obtained by means of optical techniques. Since well-known techniques will be utilized and no new measuring techniques are proposed, the techniques to be used will not be described. It may, however, be said that in non-equilibrium region information on the adjustment process can only be obtained by evaluating the shape and absolute intensity of individual spectral lines. A spectrograph of highest resolving power, such as a Fabry-Perot interferometer, is thus essential.

FUTURE PLANS

The alkali metal vapor arc tunnel has been proposed for the study of the basic phenomena taking place in the transition of a low temperature gas into one of high temperature where ionization and electronic excitation are present. The advantages of utilizing the alkali metals are, of course, not restricted to the investigation suggested in this proposal but apply equally well to basic studies of hypervelocity flow phenomena; in particular, boundary layers, ion propulsion systems, and magnetohydrodynamic problems.



IONIZATION POTENTIALS



VAPOR PRESSURES

FIG. 1

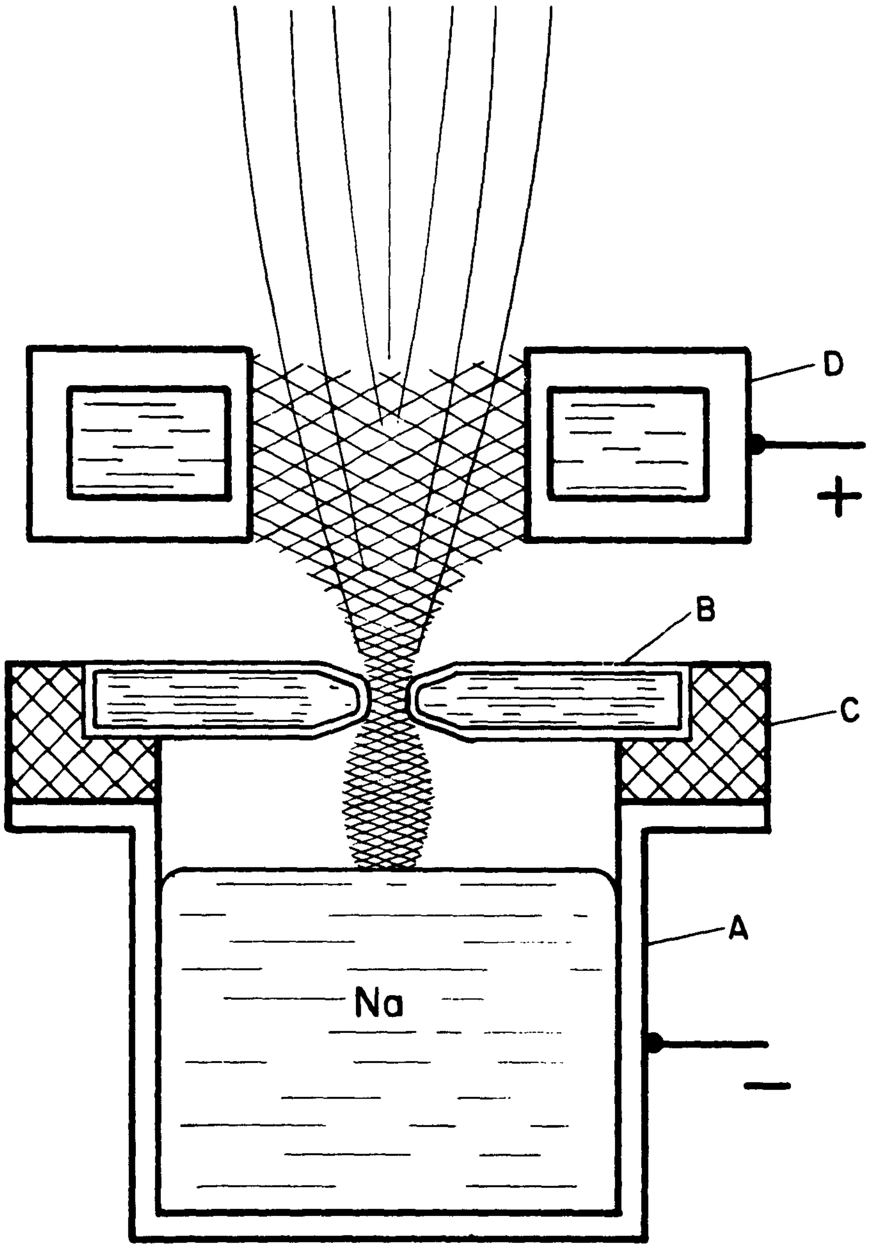


FIG. 2

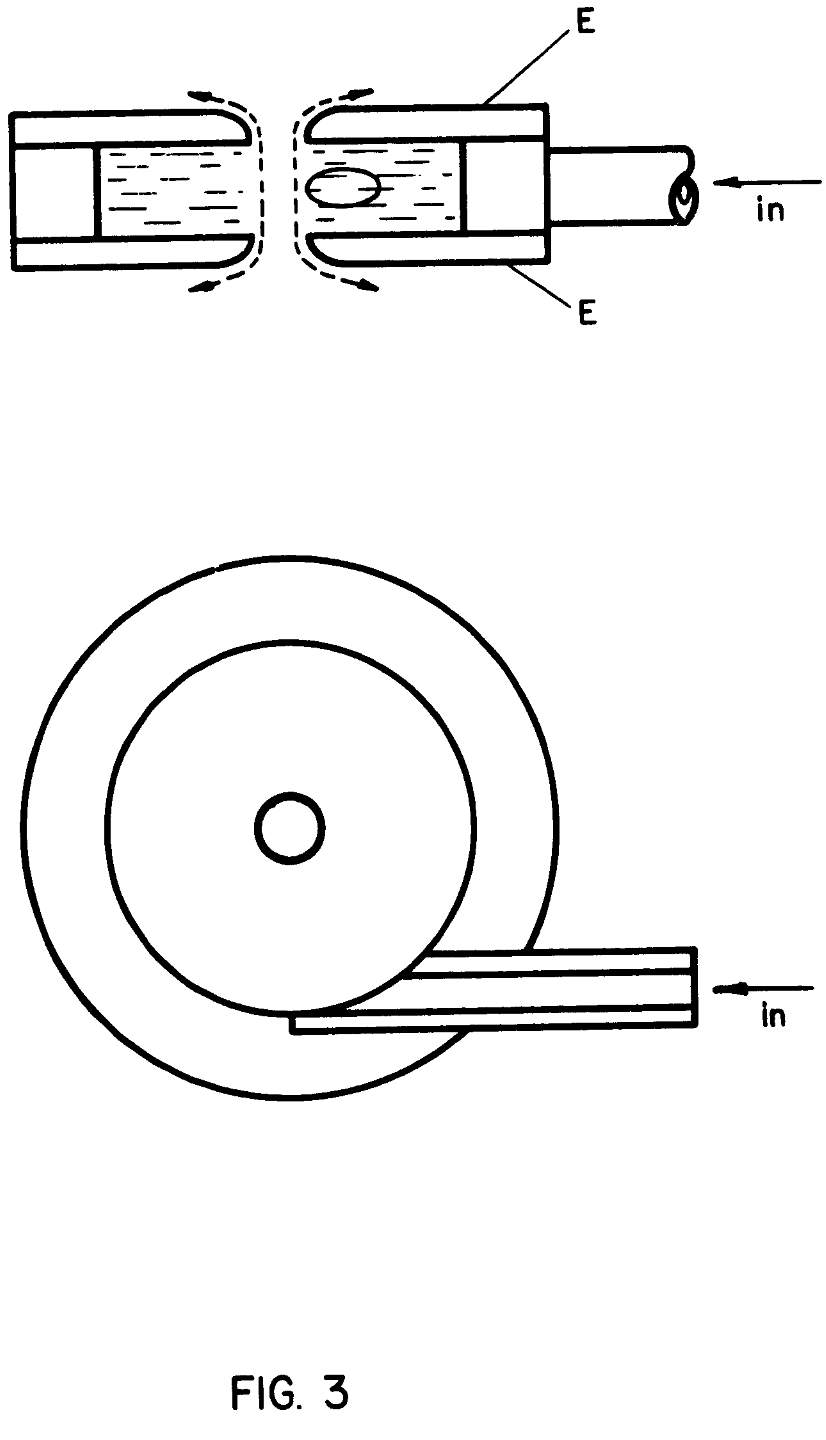


FIG. 3

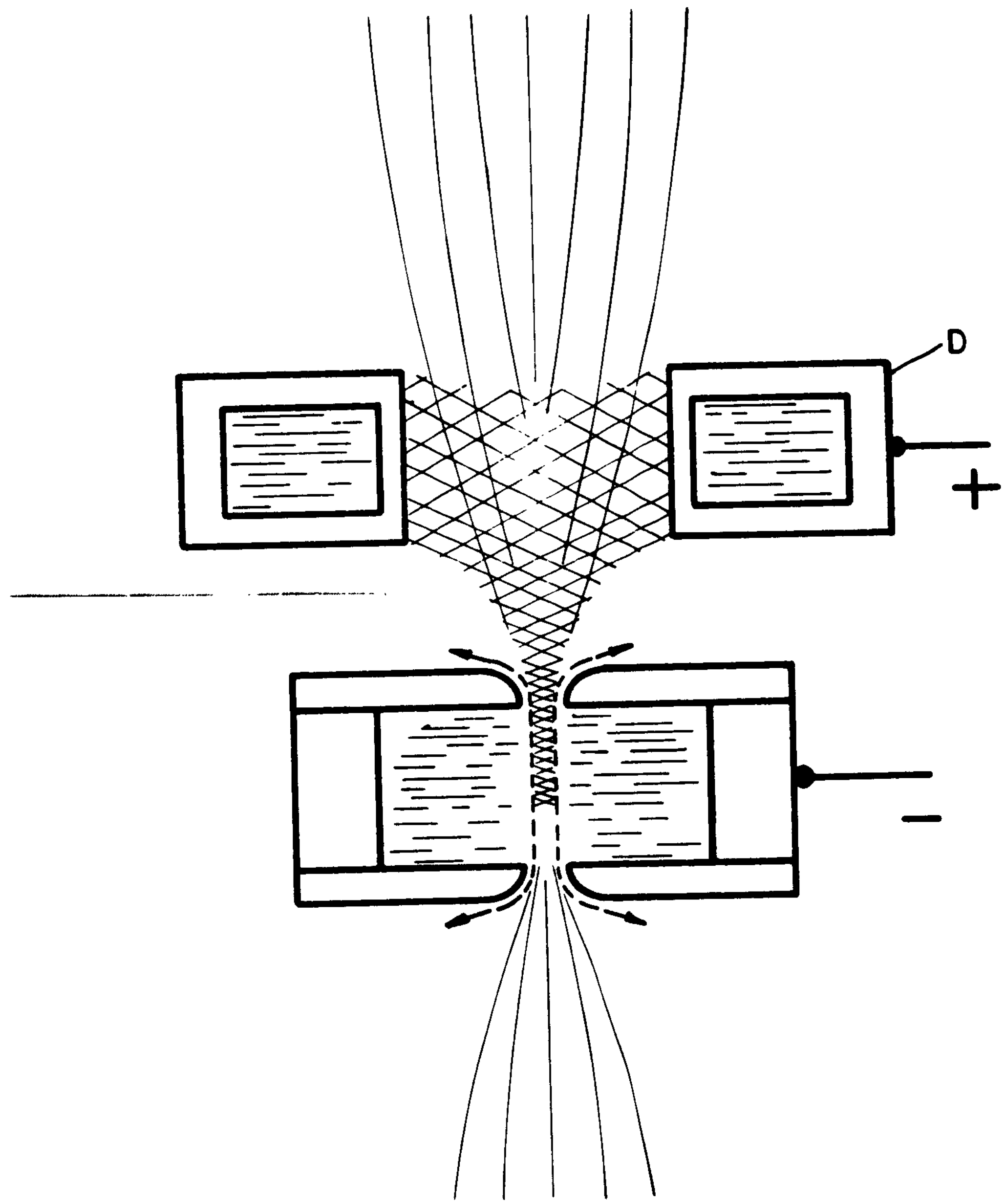


FIG. 4

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Electronic	ELEC	Arc-heated	ARCE		
Excitation	EXCI	Test facilities	TESF		
Ionization	IONI	Shock tubes	SHTU		
Shockwaves	SHWV	Wind tunnels	WINU		
Shock	SHOC	Wind tunnels (design)	WINUD		
Proposal	PRSL	Hypervelocity	HYPV		
Study	STUY	Hypersonic	HYPR		
Collisional	COLS	Measurement	MEAU		
Processes	METD	Plans	PLAG		
Gases	GASE				
Alkali metal	ALKI				
Vapor	VAPO				

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